Mars Communications Network

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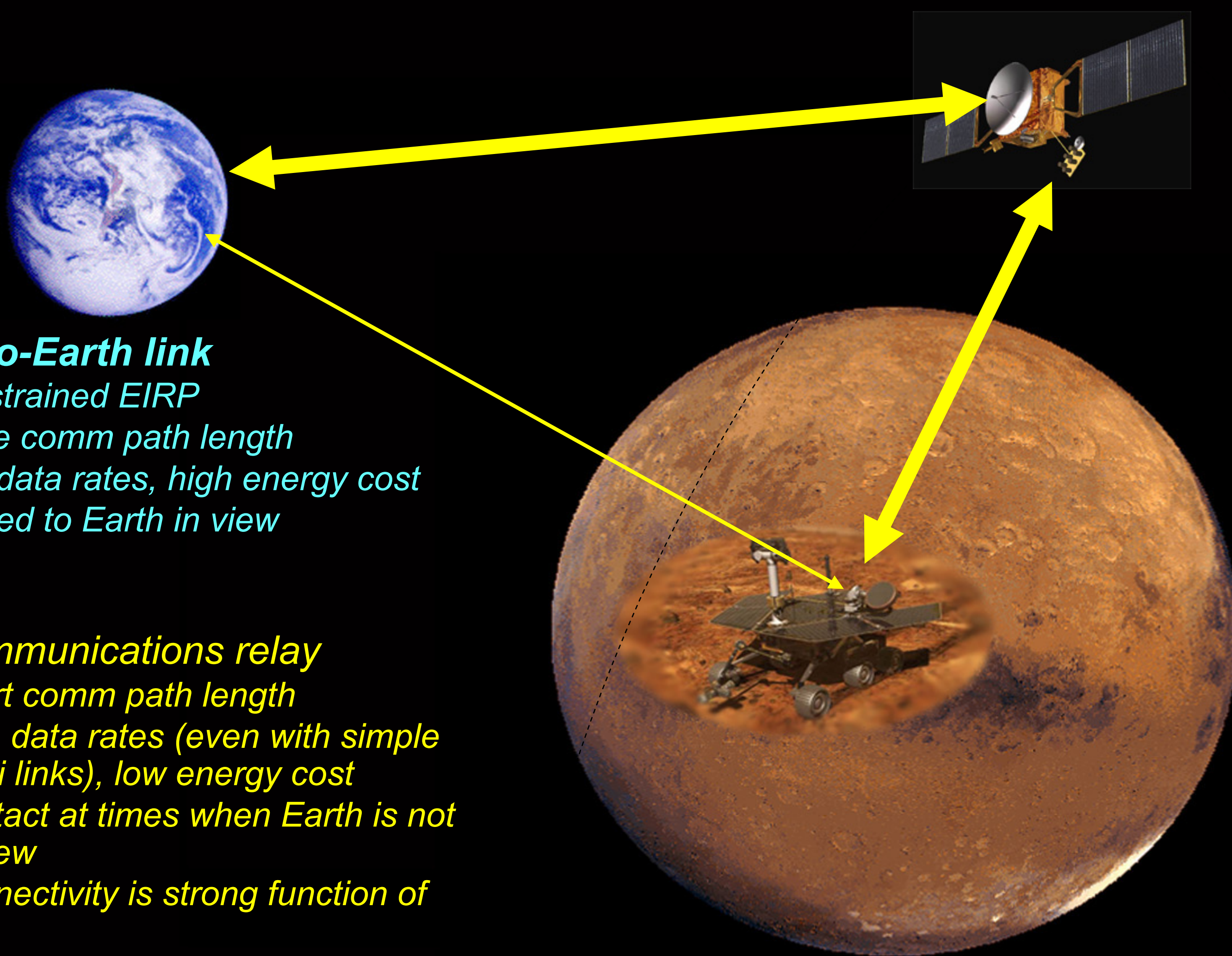
Outline

- Why we need a Relay network at Mars
- Investments needed for Mars Relay network

Relay Telecommunications

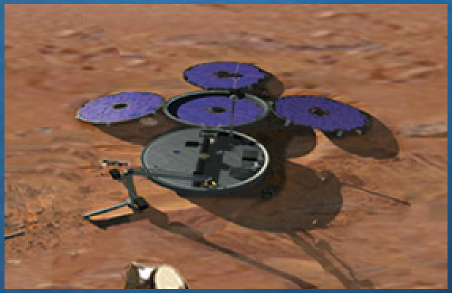


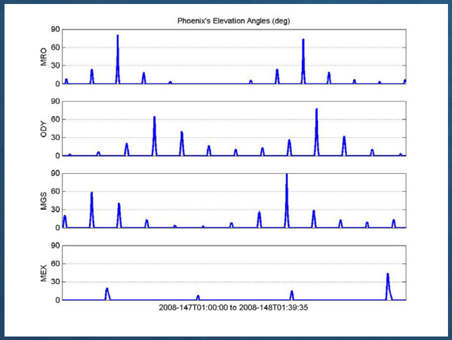
- ***Direct-to-Earth link***
  - *Constrained EIRP*
  - *Large comm path length*
  - *Low data rates, high energy cost*
  - *Limited to Earth in view*

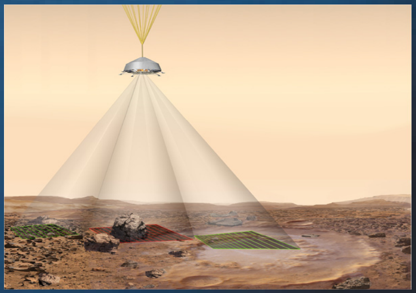
- *Telecommunications relay*
  - *Short comm path length*
  - *High data rates (even with simple omni links), low energy cost*
  - *Contact at times when Earth is not in view*
  - *Connectivity is strong function of orbit*

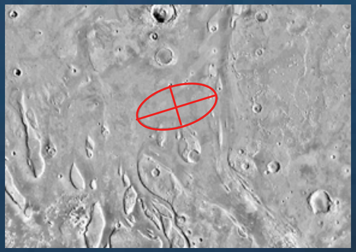
MEP Telecommunication Needs

- Increased data return
  - Augment comm bandwidth for high spatial/spectral/temporal resolution instruments
- Energy efficiency
  - Enable small, low-cost mission concepts
- Connectivity
  - Support interactive, *in situ* ops
- Critical event telemetry
  - Capture engineering telemetry during high-risk mission phases
- Radio-based navigation
  - Utilize radio metric observables on comm links for *in situ* nav



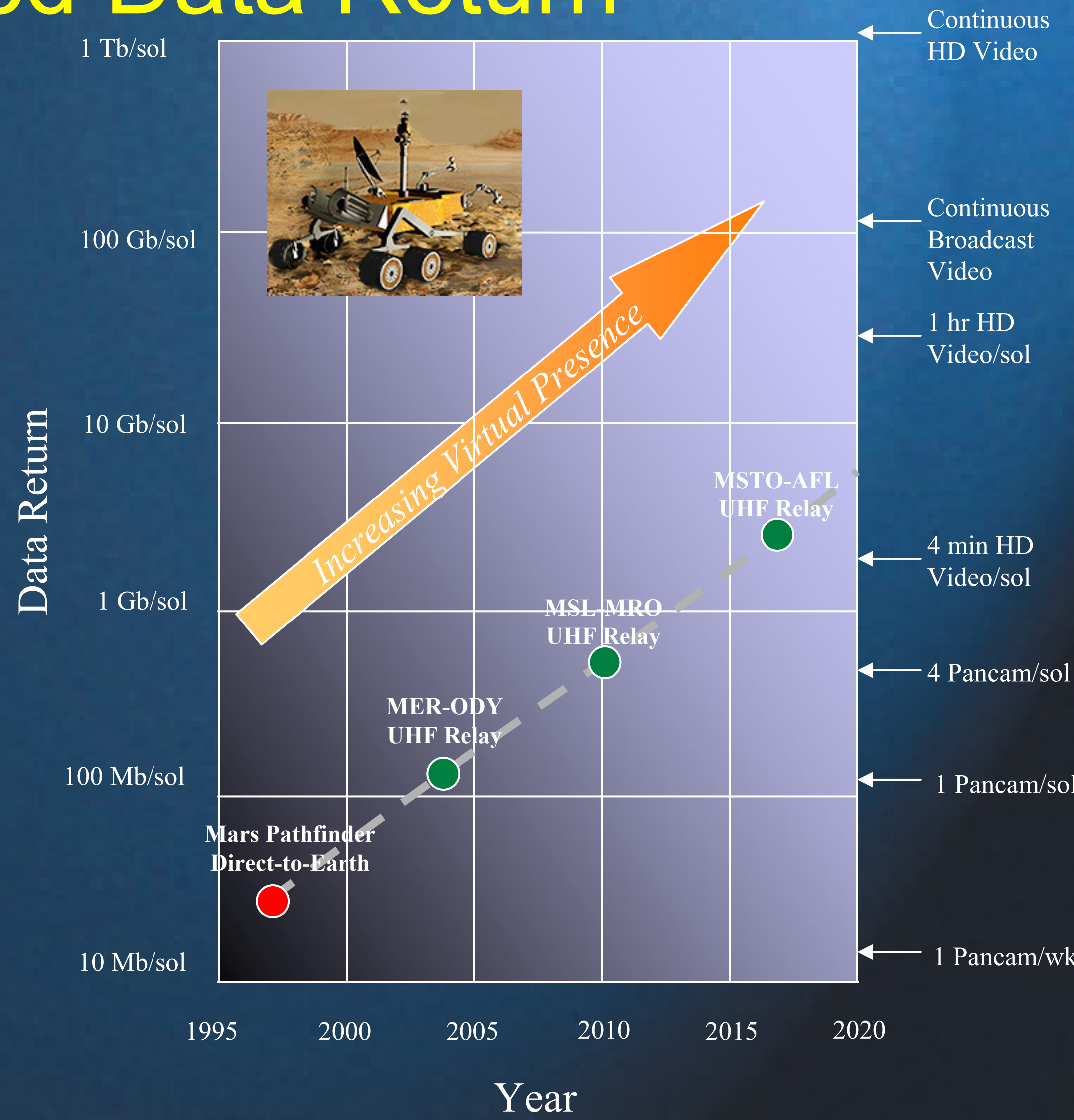




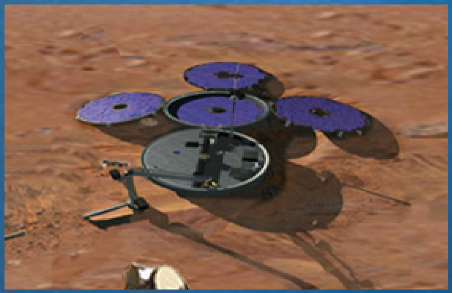


Increased Data Return

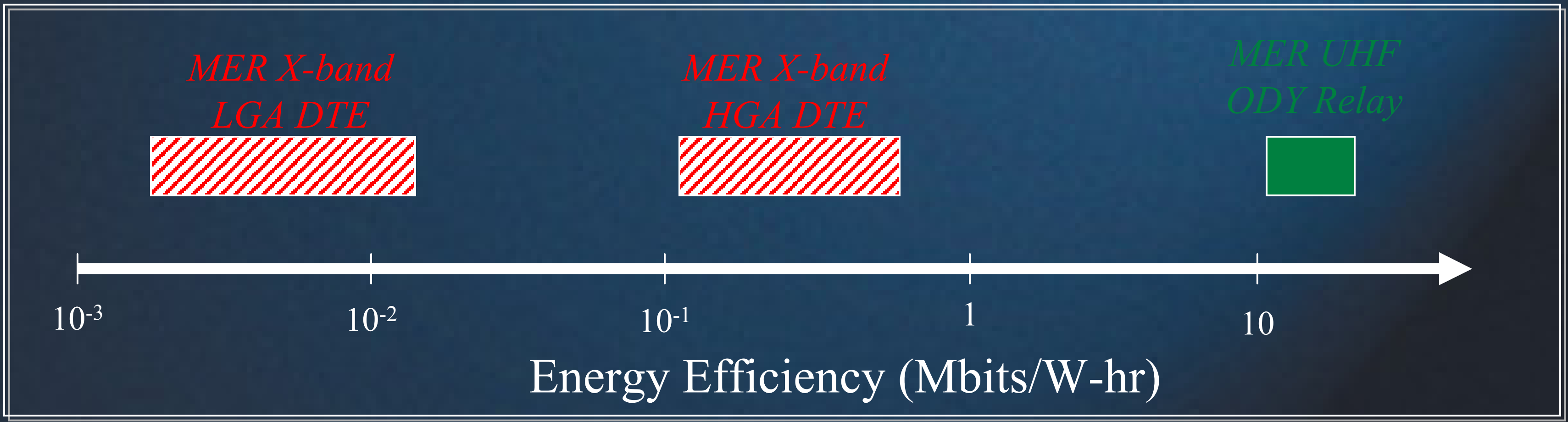
- High-resolution remote sensing instruments
  - MER (2003) Pancam
    - 0.3 mrad angular resolution; 12 filter bands distributed over two stereo apertures
    - ~10 Gb full spatial/spectral resolution data volume; ~ 0.1 - 1 Gb product data volumes in typical surface ops
  - MSL (2009) Mastcam
    - High-definition video capability
    - Will generate 2 Gbits of MPEG-compressed video in 4 min
- Increased mobility and autonomy as data rate drivers
  - Frequent change of environment
  - Increased data acquisition between ground command cycles
- Public outreach - virtual presence on Mars
  - Over 100 Million NASA web page hits for Sprit landing Jan 3-4, 2004



Energy Efficiency

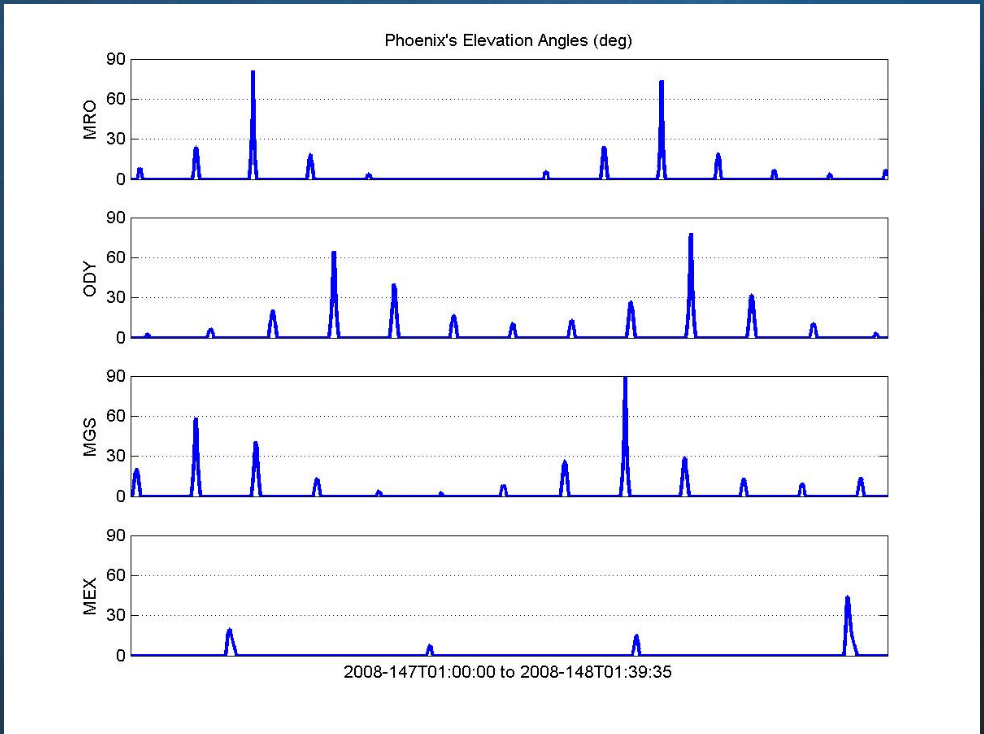


- Highly mass- and energy-constrained mission concepts are enabled by energy-efficient relay links.
  - Small landers (e.g., Beagle2, Netlanders)
  - Aerobots (ARES, Mars Balloons)
  - Microprobes (DS-2)
- Even for larger landers, efficient relay links free up energy for increased mobility & science operations.

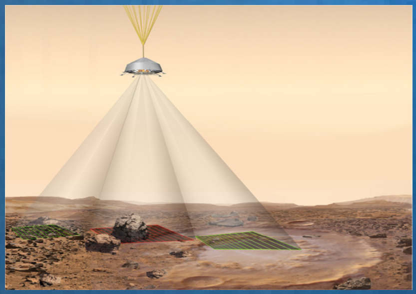


Connectivity

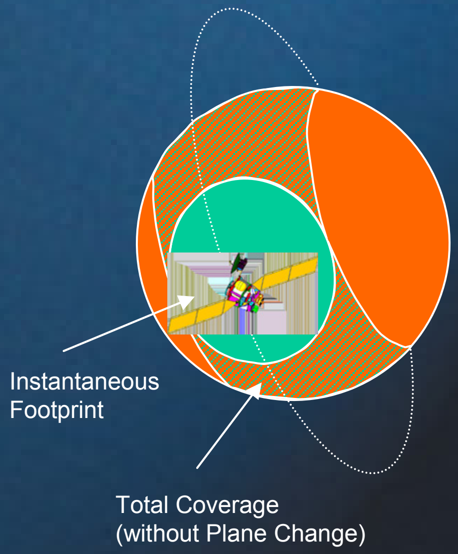
- Complexity of *in situ* operations in a dynamic and unpredictable surface environment demands frequent closure of decision loops with ground science and engineering teams.
  - Multiple command/telemetry opportunities per sol increase surface ops efficiency.
  - RTLT of ~10-40 min precludes “joystick” ops, but still allows multiple command cycles per sol.
- Relay link allows contact on night side of Mars when Earth has set.
- Relay infrastructure supports global communications, including polar regions which are seasonally out of view of Earth.



Critical Event Telemetry



- Mars Polar Lander '98 was lost during terminal descent.
  - No comm link at time of anomaly
- In response to this event, the Mars Program has established a policy of capturing telemetry during all critical mission events (e.g., EDL).
- Very limited comm capability available on DTE link if reliable low-gain link desired.
  - "Semaphores" offer effective 1 bps information rate.
- Relay orbiter can support much higher-rate low-gain link, but requires relay asset satisfying temporal *and* spatial constraints.
  - Kbps-class links supportable with "omni" links

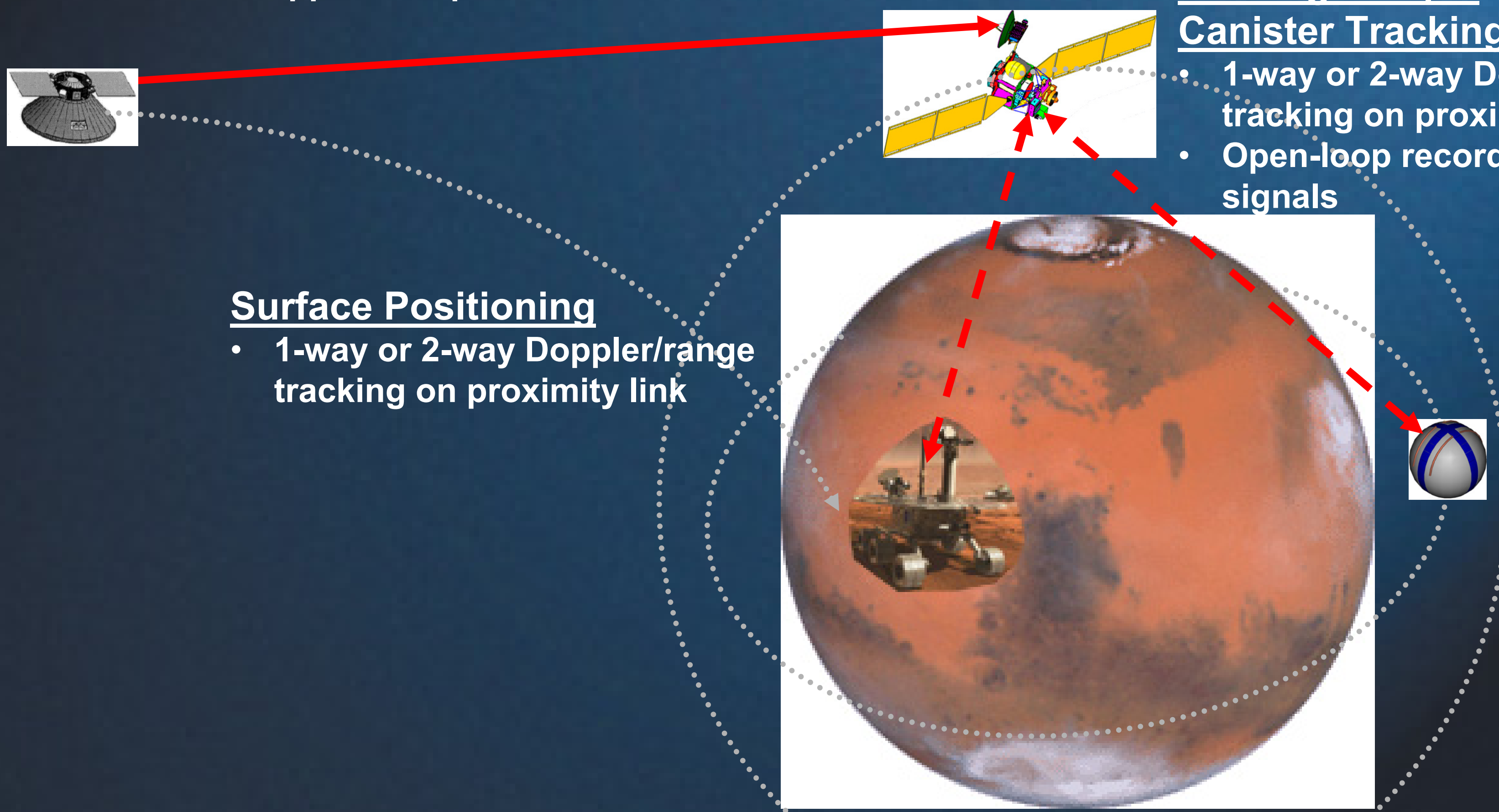


Radio-Based Navigation

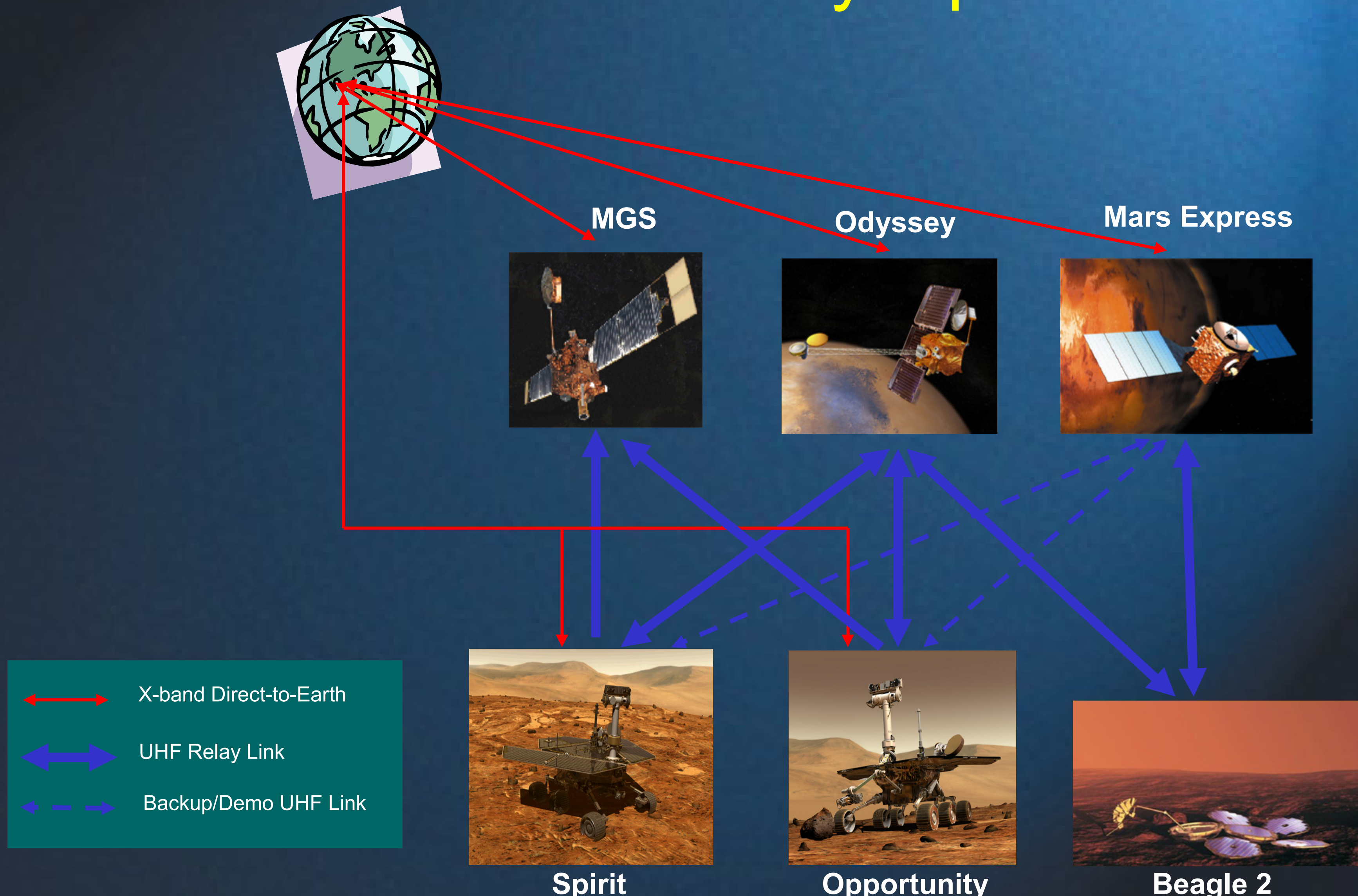
Precision Approach Navigation
- Doppler/range on RF link between approach spacecraft and orbiter

Orbiting Sample Canister Tracking
- 1-way or 2-way Doppler tracking on proximity link
- Open-loop recording for weak signals

Surface Positioning
- 1-way or 2-way Doppler/range tracking on proximity link

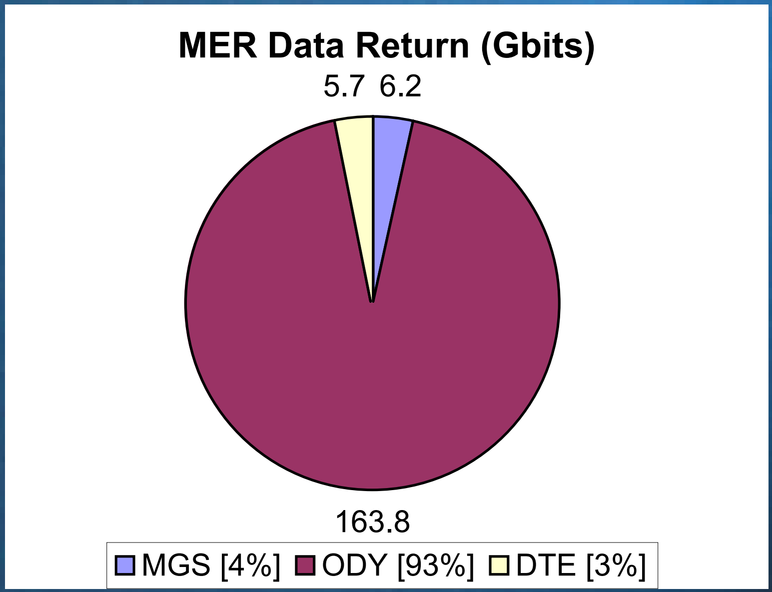


2003/2004 Mars Relay Operations

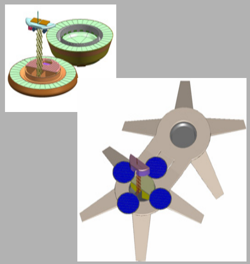


Relay Telecommunications for MER

- Increased data return
  - Spirit and Opportunity have returned over *175 Gb* of data (compare to 3 Gb for Mars Pathfinder)
    - *97% of MER data return* has come via the ODY and MGS UHF relay paths
- Energy efficiency
  - *20 - 200x increase* in Mb/W-hr for UHF relay vs. X-band DTE
- Critical event telemetry
  - *8 kbps* UHF link to MGS during EDL (vs. ~*1 bps* X-band DTE link)
- Radio-based navigation
  - *<10 m* position determination in Martian reference frame, based on Doppler measurements on UHF relay link



Second-Decade Landed Mission Concepts

	Mars Science Laboratory	ExoMars (ESA)	Astrobiology Field Laboratory	Geophysical Network Landers	Mars Sample Return (Rover)	Mid-Rover Mars Missions
Agency	NASA	ESA	NASA	NASA	NASA	NASA
						
Mission Concept	a roving long-range, long-duration science laboratory that will study the Martian surface and pave the way for a future sample return mission.	a pair of lander and rover to characterize the biological environment and to search for life on Mars	a MSL-derivative rover to search specifically for biological evidence and identify it with confidence using sophisticated in-situ robotic instruments	landers will measure conditions at their locations on the surface, seismic activities, meteorology, the planet's internal structure, and its magnetism	a pair of lander and rover to study and collect samples, load sample into Mars ascent vehicle for Earth return	Mid-size rovers to carry out scientific investigations of Mars in areas (such as the planet's geochemistry or internal structure)
Launch/Arrival:	LD: 9/15/09-10/4/09 AD: 7/10/10-9/22/10	LD: May 2011 AD: June 2013	2nd Decade	2nd Decade	2nd Decade	2nd Decade
Mission Duration:	1 Martian Year	Rover: 180 Sols Lander: 6 yrs	1 Martian Year	1 Martian Year	< 6 months (surface)	90-Sol
Exploration Type:	Large Roving Laboratory	Small Lander with Mid-size Rover	Large Roving Laboratory	4-6 Fixed Landers	Lander with Earth Return Vehicle and MER-Class Rover	MER-like Rovers
Landing Site:	+/-45 deg latitude	-15 to +45 deg latitude	-55 to +70 deg latitude	+/-80 deg latitude	+/-45 deg latitude	TBD
EDL Comm:	X-band + UHF	UHF + X-band(Backup)	UHF	UHF	UHF	TBD
Surface Comm:						
-Forward Link	UHF relay & X-band DFE	UHF relay & X-band DFE (Backup Command)	UHF	UHF	TBD	UHF
-Return Link	UHF Relay & X-band DTE	UHF Relay & X-band DTE (Emergency Telem)	UHF	UHF	TBD	UHF
X-band Radio:	SDST, MER-class RFS (15 W SSPA, 28 cm HGA)	NA	TBD	None	Lander has SDST w/LGA	None
UHF Radio:	Electra-lite	TBD	Electra-lite	Electra-Lite	Electra-Lite on both Lander and Rover	Electra-Lite
Return Link Data Volume Requirements	250-1000 Mb/sol	250-1000 Mb/sol (Rover) 50-100 Mb/sol (Lander)	250-1000 Mb/sol	40-50 Mb/sol/lander	100-250 Mb/sol (Rover) 50-100 Mb/sol (Lander)	100-250 Mb/sol

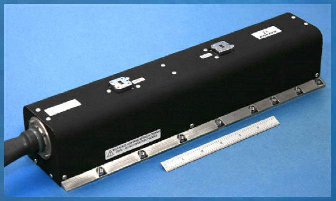
Electra Enhancements

- Electra's software radio architecture provides an opportunity to significantly improve MRO's relay capabilities.
  - *Partially compensates for loss of relay capabiltiy due to MTO cancellation.*
- Three performance enhancement options:
  - Implement adaptive data rates (under development in MTP).
  - Increase highest available data rate (from 1 Mbps to 4 Mbps).
  - Add Reed-Solomon error-correcting codes.

	Adaptive Data Rates	Add 4 Mbps upgrade	Add Reed Solomon Coding
Performance Benefit	2.0 dB *(>50% improvement)*	3.1 dB (total) *(~2x improvement)*	3.9 dB (total) *(~2.5x improvement)*
Implementation Cost	$40K	Add'l $185K	Add'l $250K

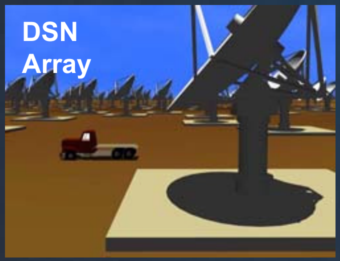
Given the enormous benefit-to-cost ratio, we strongly recommend implementing all three of these options on MRO.

Deep Space Links



180W Ka-band TWTA

- High-resolution remote sensing orbiters will drive the need for high-rate orbiter downlinks.
  - MRO will only map <1% of Mars at full HiRISE capability due to current data rate limitations.
  - Limited X-band spectrum motivates continued migration to Ka-band.
- MSL-class landers will utilize DTE/DFE links for increased contact opportunities and backup to relay.
- Potential DSN Array upgrade, combined with emerging spacecraft telecom technologies, offer 10-100x improvement in 2nd-decade DTE capabilities.



Direct-to-Earth Downlink Data Rate Capability

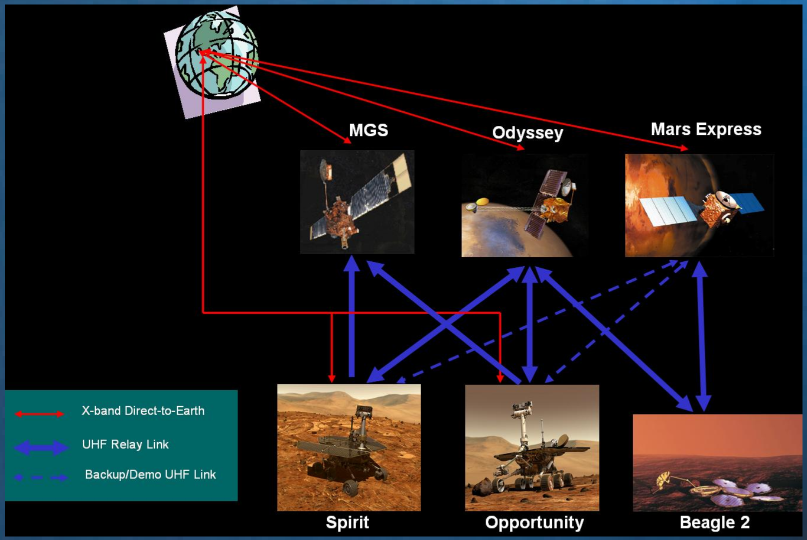
	MER-class	MRO-class		MRO+
	X: 15 W/28 cm	X: 100 W/3 m	Ka: 35 W/ 3m	Ka: 180 W/3 m
34m	0.0005	0.5	0.3	1.7
70m	0.002	2.1 *	n/a	n/a
Array (180 x 12m)	0.011	11.2 *	7.4	38.2

(@2.7 AU Earth-Mars Distance)

*X-band spectrum limits symbol rate to 6.2 Msps, assuming bandwidth-efficient GMSK modulation

Automation

- Mars operations in 2003/2004 encompassed 13 potential links, each requiring scheduling, data selection, data rate management – all done manually.
- Mars ops in the 2020s could involve four orbiters, eight landers, forty or more links.
- Automated network protocols simplify operations, enabling networks to scale up.
  - CFDP store-and-forward overlay.
  - Delay-tolerant networking protocols.



<table>
<tr><td colspan="4">User application</td></tr>
<tr><td></td><td colspan="1">File Transfer</td><td colspan="2">Asynchronous Messaging</td></tr>
<tr><td colspan="4">Bundle Protocol (intra-DTN routing)</td></tr>
<tr><td colspan="2">LTP (retransmission)</td><td colspan="2">TCP (retransmission)</td></tr>
<tr><td colspan="2">CCSDS encapsulation packets</td><td colspan="2">IP (intra-Internet routing)</td></tr>
<tr><td>CCSDS AOS</td><td colspan="2">CCSDS Prox-1</td><td>Ethernet</td></tr>
<tr><td colspan="3">R/F, optical</td><td>wire</td></tr>
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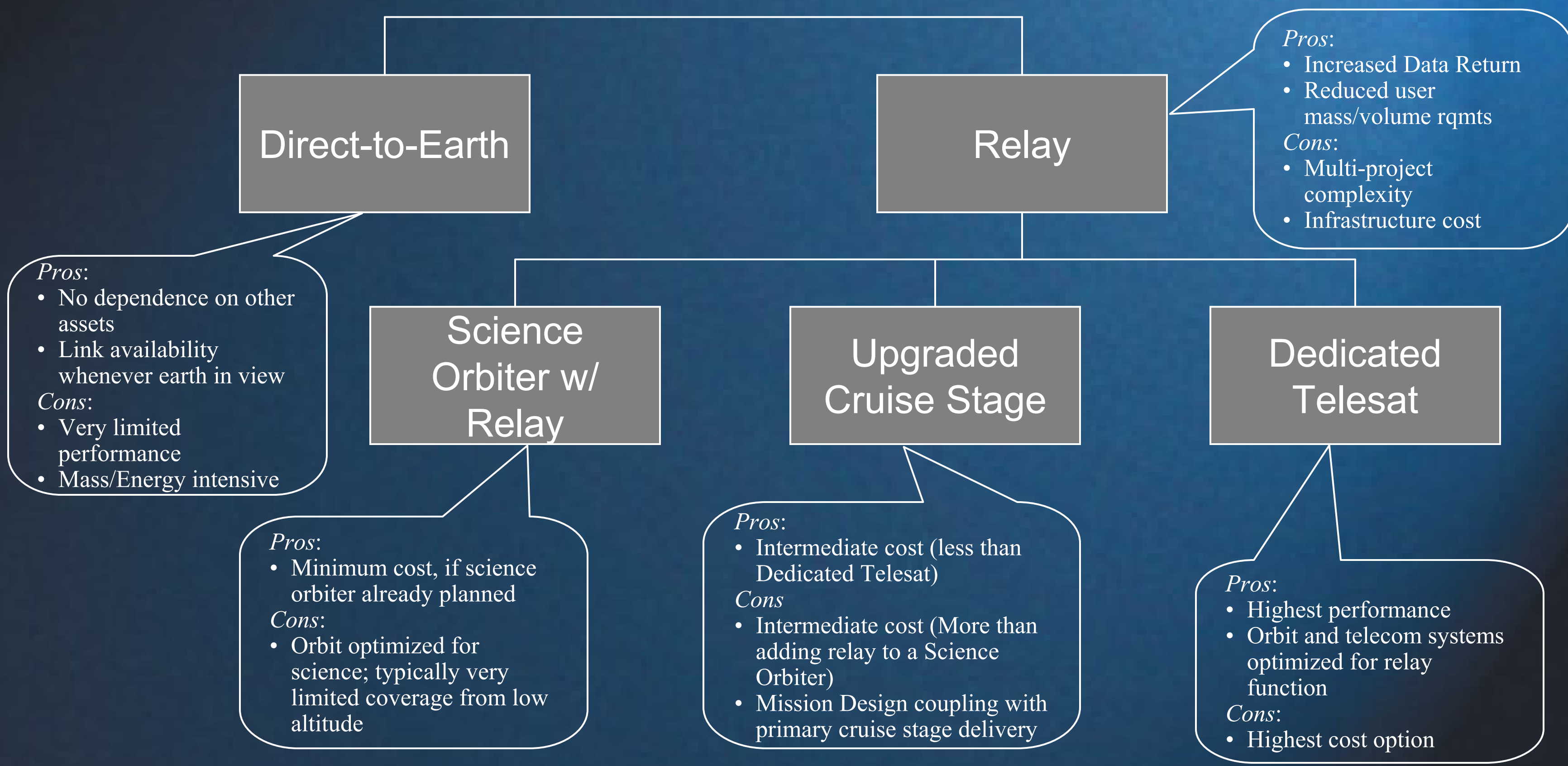
Mars Telecommunications Options



- Current Mars Robotic program telecom strategy:
  - Grow & sustain relay infrastructure based on periodic launch of long-lived relay-equipped science orbiters
  - Augment large landers with DTE for risk mitigation & flexibility

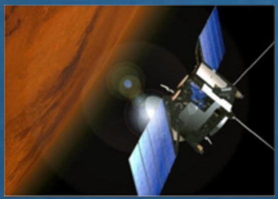
Mars Relay Network Orbiters

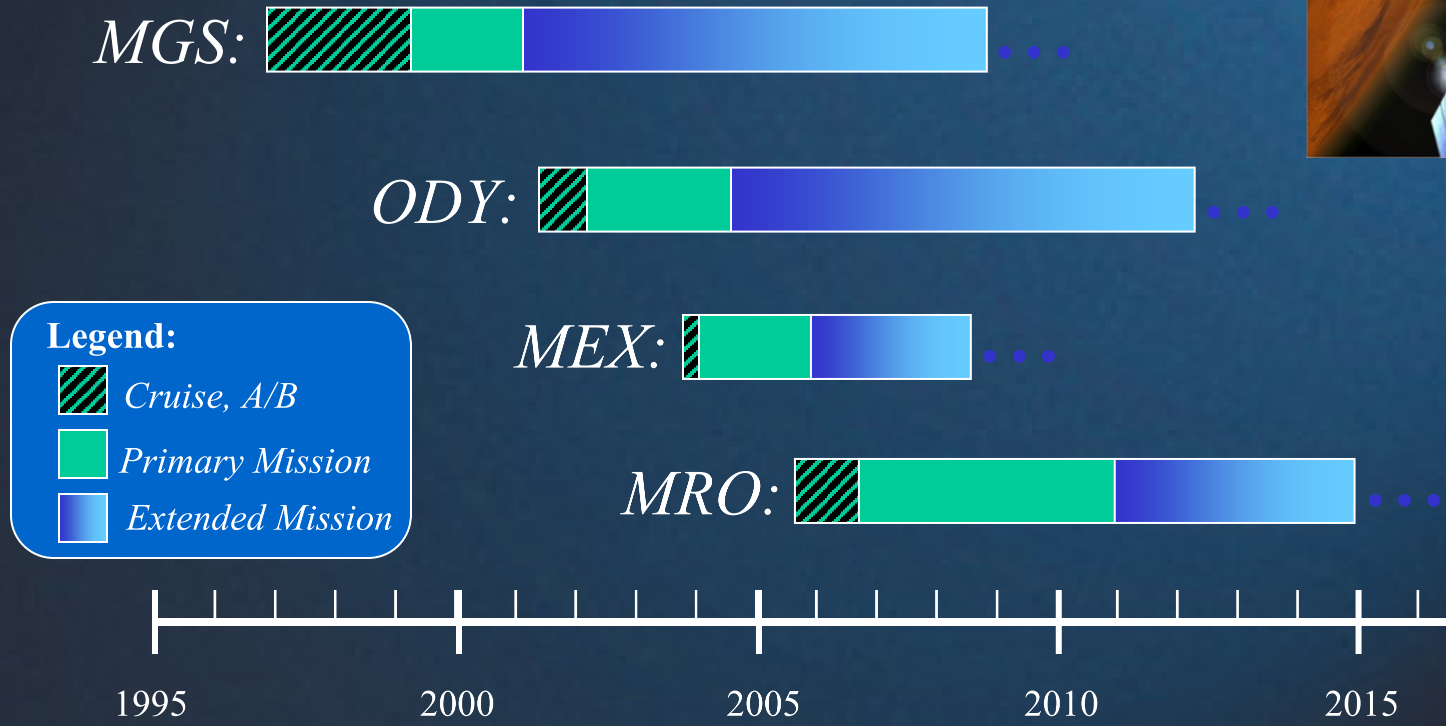
   

	Mars Global Surveyor	Mars Odyssey	Mars Express	Mars Reconnaissnace Orbiter
Agency:	NASA	NASA	ESA	NASA
Launch:	Nov. 8, 1996	April 7, 2001	June 2, 2003	Aug, 12, 2005
Mars Orbit Insertion:	Sep. 11, 1997	Oct. 24, 2001	Dec. 24, 2003	Mar, 2006
Orbit Characteristics:	~400 km circular sun-synch ~2 PM asc node 93 deg inclination	~400 km circular sun-synch ~5 AM asc node 93 deg inclination	250 x 10,142 km elliptical non-sun-synch 86.3 deg inclination	255 x 320 km sun-synch ~3 PM asc node 93 deg inclination
UHF Radio:	Mars Relay (CNES)	CE-505	Melacom	Electra
Link Protocol:	Mars Balloon Relay (MBR)	CCSDS Proximity-1	CCSDS Proximity-1	CCSDS Proximity-1
Forward Link:				
- *Frequency*	437.1 MHz	437.1 MHz	437.1	435-450
- *Data Rates*	n/a (MBR tones only)	8 kbps	2, 8 kbps	1,2,4, É , 1024 kbps
- *Coding*	n/a	uncoded	uncoded	uncoded or 7,1/2
Return Link:				
- *Frequency*	401.528711 MHz	401.585625 MHz	401.585625 MHz	390-405
- *Data Rates*	8, 128 kbps	8, 32, 128, 256 kbps	2,4, É ,128 kbps	1,2,4, É , 1024 kbps
- *Coding*	(7,1/2) Convolutional	(7,1/2) Convolutional	(7,1/2) Convolutional	(7,1/2) Convolutional

Relay Infrastructure Robustness

- Existing set of orbiters provides robust coverage through current decade, but will require replenishment in the second decade

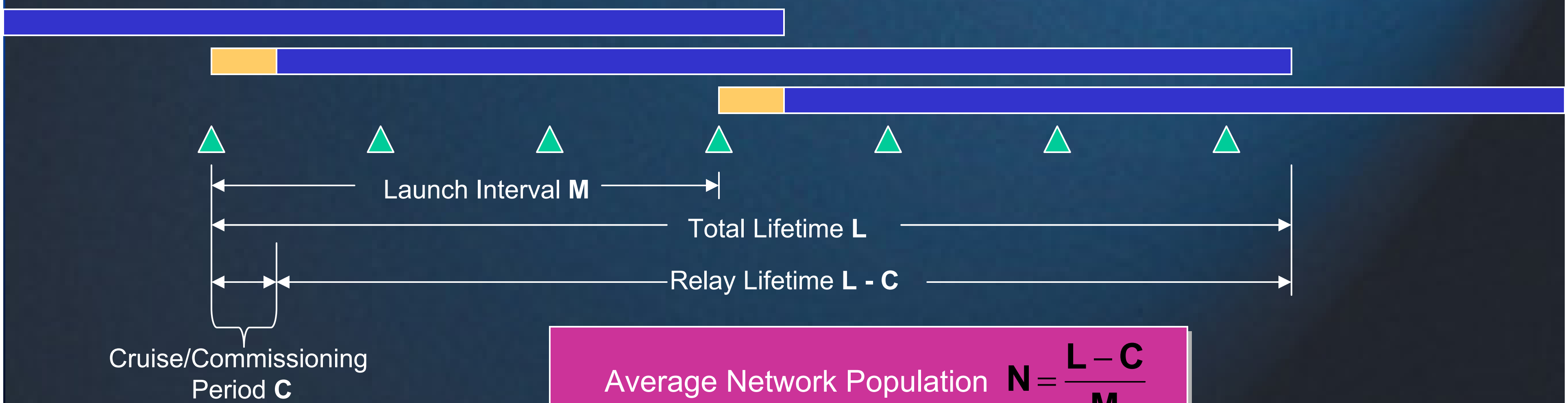




Relay Orbiter Replenishment

- A robust infrastructure strategy would maintain a *nominal* population of at least 2 orbiters over time.
  – Avoids single-point failure for relay-dependent missions.
- Relay network occupancy will be a function of *lifetime* and *launch rate.*
  – Launching an orbiter every 3rd opportunity requires >10 yr lifetime to maintain redundant relay assets.

Assumes 12-month Cruise/Commissioning Period



Average Network Population $\mathbf{N} = \frac{\mathbf{L} - \mathbf{C}}{\mathbf{M}}$

Preliminary Architecture Comments

Initial architecture assessment based on nominal 10-year lifetime for each relay orbiter:

Redundant MRO/ODY support for MSL

'11/'13 Orbiter provides relay coverage for '16, '18, '20 opportunities

No residual feed-forward relay assets

2009	2011	2013	2016	2018	2020	2022	2024
MSL	Scout	Mars Science Orbiter + Telecom	Mid-rovers (2)	Scout	Planetary Evolution & Meteorology Network	MSR Orbiter + ERV	MSR Mobile Lander
	or		or				
	Mars Science Orbiter + Telecom	Scout	AFL				

MSR Orbiter can support MSR lander

'01 ODY …

'05 MRO …

'11 Sci/Telecom Orbiter …

'13 Sci/Telecom Orbiter …

'22 MSR Orbiter

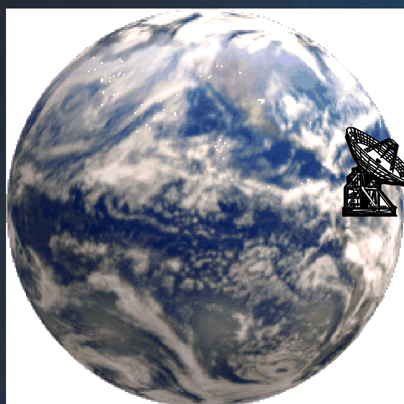
Program should place high priority in achieving >10 yrs operational lifetime from ODY and MRO, in order to provide more robust, redundant relay support to 2nd-decade missions

Summary of Investments Needed

- Upgrade Electra on-board UHF radios for communication between landed vehicles and relay orbiters.
- Upgrade DTE capability – Ka-band radios and DSN Array – for communication between relay orbiters and Earth.
- Automate network operations, using advanced protocols.
- Assure robust relay infrastructure by maintaining a Mars mission launch program that replenishes relay orbiter capability.

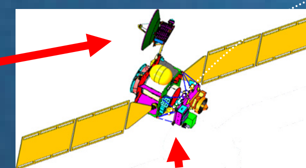
Backup

Key Aspects of Relay Communications



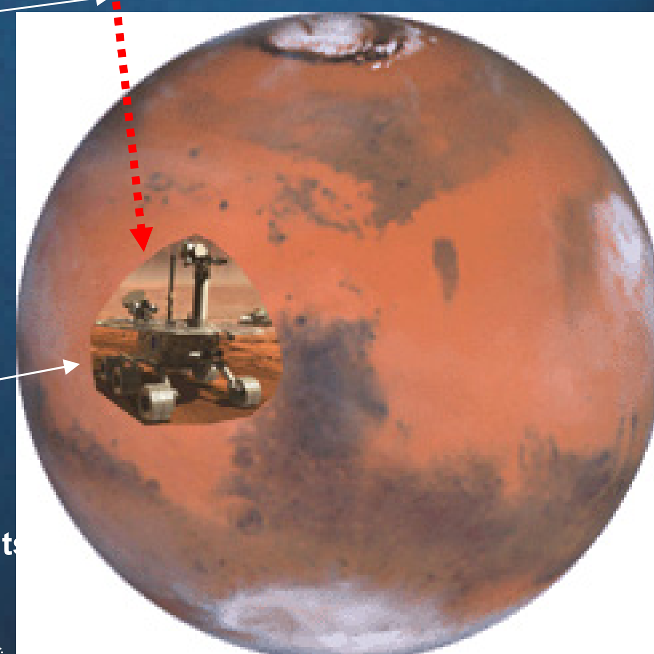
Orbiter Deep Space Link:
- Data rate (~power x gain)
- Frequency (X, Ka)
- Range variation (25x comm performance)

Orbit:
- Slant range
- Connectivity
- Global Coverage



Orbiter Proximity Link:
- Data Rate
- Antenna gain/steering

Proximity Link:
- Frequency band
- Comm protocols
- Multiple Access Scheme



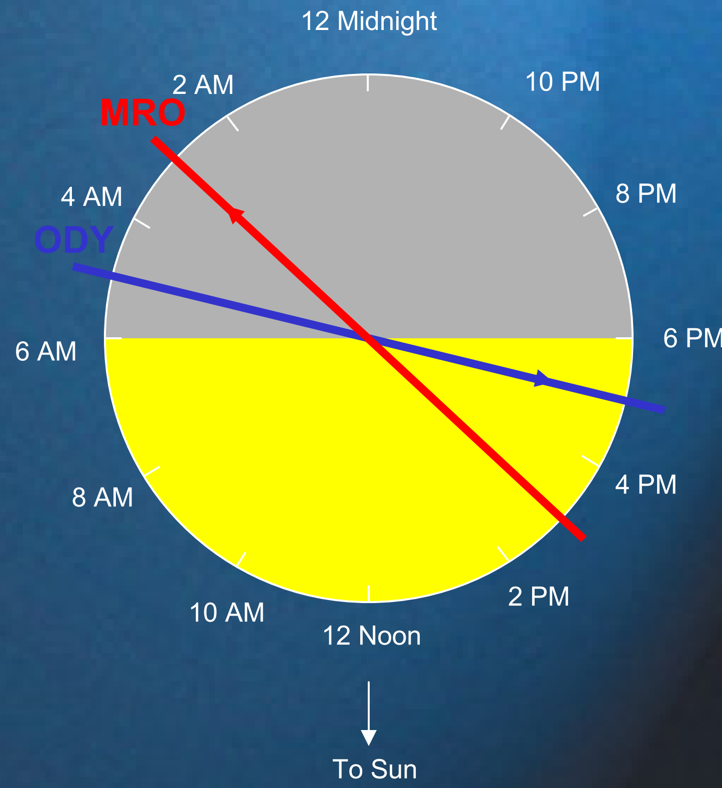
User:
- Transmit power
- Antenna gain/steering
- Power/energy constraints

Relay Orbiter Lifetime: Fuel

- ODY and MRO both have significant fuel reserves, with potential for operation beyond 2020
- Both projects are considering science-driven options that would shorten potential extended mission lifetime
  - ODY: Move to 3 PM LMST for improved THEMIS imaging
  - MRO: Extend ops in low-altitude Primary Science Orbit
- Recommend adopting fuel use strategies that allow for ODY/MRO ops through second decade

Relay Orbit Evolution

- Local time of MRO and ODY orbit planes determine contact times for surface relay support and critical event coverage times
- Odyssey
  - Currently operating at 5 PM LMST descending node
    - THEMIS prefers orbit plane towards noon, while GRS prefers orbit plane towards terminator
  - S/C bus energy constraints preclude ops between ~10 AM - 2 PM LMST due to eclipse duration
  - Move to 3 PM LMST (2008-2011) is under consideration for THEMIS science considerations
    - Potentially impacts relay performance by reducing diversity of ODY+MRO contact times and reducing aggregate ODY+MRO critical event coverage

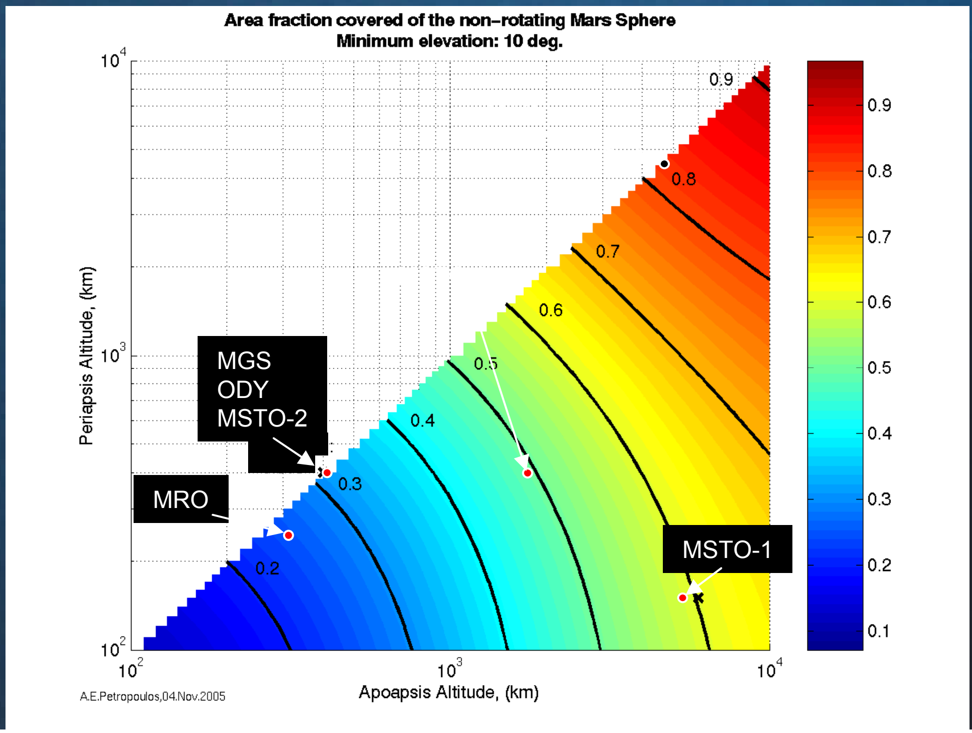


- MRO
  - Primary Science Phase designed for 3 PM LMST
    - Compromise between HiRISE and CRISM optimal viewing geometries
    - MCS desires constant LMST to identify long-term seasonal atmospheric effects
  - Spacecraft could operate in ~2-5 PM LMST range and still maintain orientation for science observing
  - In principle, MRO could operate at any LMST in inertial mode
- Recommend program-level science/telecom trade to finalize orbit strategy

Critical Event Coverage

- Successful capture of high-rate telemetry during critical events requires relay asset at the right place, right time
- Low-altitude science orbiters provide limited coverage relative to high-altitude telesat like MTO
  - MSTO can provide intermediate level of coverage during elliptical orbit phases

- Lander missions can attempt to tailor mission design (LD/AD) to enable coverage w/ existing orbiters
  - MSL has done this for 2009, allowing MRO EDL coverage over full +-45 deg latitude range
  - Can drive increase in C3 and/or V_{inf}
- Have performed initial analysis of all 2nd-decade opportunities to examine arrival geometries and potential for critical event coverage
  - Initial results are encouraging, suggesting that large latitude ranges can be targeted with critical event coverage and acceptable C3, V_{inf} costs



Mars Science & TelecomOrbiter (MSTO)

Mission Objectives

Multiple science objectives
- Aeronomy
- Trace Gas
- Executed in consecutive science orbits

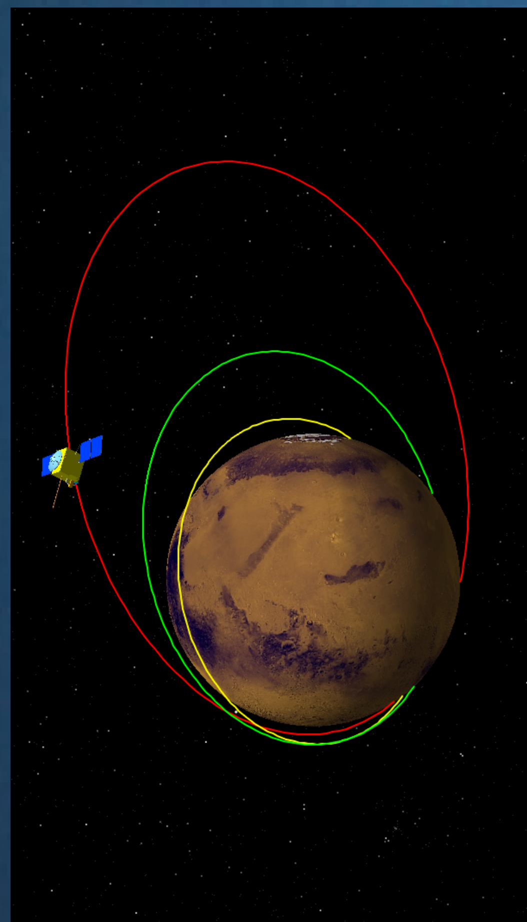
Long-term (multiyear) observation
- Approximate 11-year solar cycle

Infrastructure for future missions:
- Critical event coverage
- Science data relay
- 10 years telecommunications

Feed Forward for future missions:
- Definition of aerobraking and aerocapture environments

Instruments/Payload

- 80-100 kg
- 7 to 10 instruments



MSTO orbit:
- *Science Phase 1 (red)*
- *Science Phase 2 (yellow)*
- *Telecom Infrastructure Phase (green)*

Mission Scenario

MOI
- 300 km x 34000 km
- Inclination 75 deg

Aerobraking Phase I
- Duration: ~7 months

Science Phase I
- Duration: 1 year
- 150 km x 6500 km

Aerobraking Phase II
- Duration: 2.5 months

Science Phase II
- Duration: 1 year
- 400 km x 400 km

Telecom Infrastructure Phase
- Duration: 8 years
- 400 km x 2000 km

Mission Options

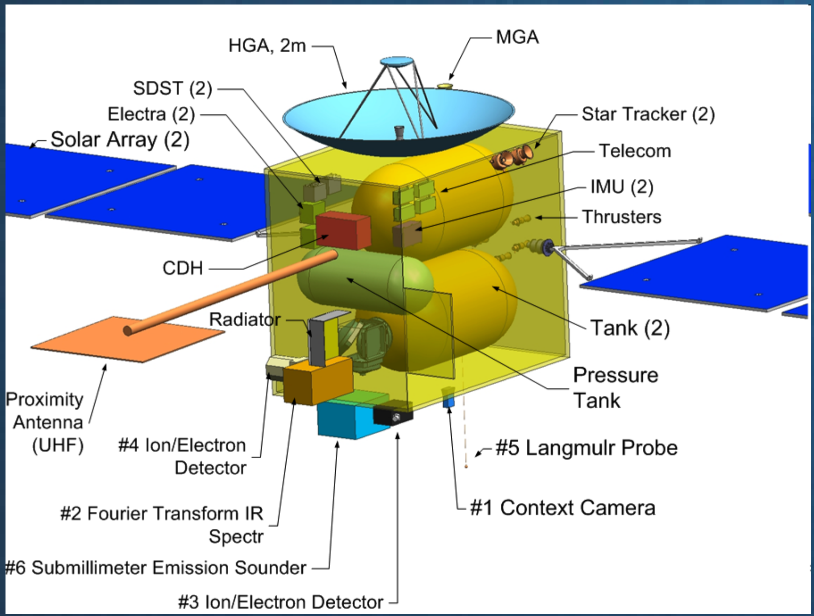
- 2011 Opportunity
  - LD: Oct 18-Nov 6, 2011
  - AD: Sep 3-Sep 9, 2012
- 2013 Opportunity
  - LD: Nov 21-Dec10, 2013
  - AD: Sep17-Sep 29, 2014

Mars Science & Telecom Orbiter (MSTO)

– Characterize the upper atmosphere of Mars
– Determine how the solar wind interacts with the upper atmosphere and ionosphere
– Define the aerobraking and aerocapture environments for future Mars exploration

Example Instruments

– Camera
– Fourier Transform Spectrometer
– Submillimeter Emission Sounder
– Ion/electron Detector
– Ion/neutral Mass Spectrometer
– Langmuir Probe
– Magnetometers



Technology

–UHF Antenna
–S/C Thermal Subsystem for low-T instruments (80K)
–Adaptation of aeronomy instruments to Mars atmosphere

Mass Summary*

–S/C Dry Mass CBE	755 kg
–Payload CBE	81 kg
–S/C Monoprop Load	1361 kg
–Wet Mass	2557 kg

Trajectory*

–Type II
–C_3 of 12.6 km^2/s^2
–Flight time 10 months
–Arrival $V\infty$ 2.78 km/s

Launch Vehicles

–Atlas V-401 (cap.= 2695 kg)
–Delta IV 4450 (cap. = 3465 kg)

**Mission design info for 2011 opportunity; 2013 launch would require LV upgrade*